

# Nearby, Thermally Emitting Neutron Stars

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**Abstract.** We describe a sample of thermally emitting neutron stars discovered in the *ROSAT* All-Sky Survey. We discuss the basic observational properties of these objects and conclude that they are nearby, middle-aged pulsars with moderate magnetic fields that we see through their cooling radiation. While these objects are potentially very useful as probes of matter at very high densities and magnetic fields, our lack of understanding of their surface emission limits their current utility. We discuss this and other outstanding problems: the spectral evolution of one sources and the relation of this population to the overall pulsar population.

**Keywords:** neutron stars, pulsars

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## INTRODUCTION

While almost 2000 isolated neutron stars have now been discovered as radio pulsars, the total number in the Galaxy is much larger. Radio pulsars emit pulsations for  $\sim 10^7$  yr and are visible due to radio beams that subtend 1–10% of the sky, so the total number of neutron stars of all ages just in the local region of the Galaxy (where radio pulsars are detectable) should be  $\gtrsim 10^6$  [e.g., 1, 2].

Are those neutron stars not detectable as radio pulsars objects invisible, or is there some chance of observing them (there is always the exception of Geminga, where we see no radio emission but is otherwise a standard pulsar)? For years astronomers have proposed that a large fraction of these objects would be visible through one of two mechanisms: accretion [3–5] or cooling [6]. The first mechanism could revive old, dead pulsars, while the second would primarily work for younger sources. Both mechanisms, however, make the neutron stars visible in the soft X-ray regime, not in the radio regime that had dominated the study of neutron stars.

These neutron stars should be identifiable by [4]:

1. Largely thermal emission peaking in the soft X-ray or far-UV band, requiring small hydrogen column densities to remain visible
2. The absence of bright optical counterparts
3. Significant ( $\gtrsim 0.1$  arcsec yr $^{-1}$ ) proper motions
4. Preferred locations in the Galactic plane

The first two criteria relate to the spectra of the neutron stars, and serve to rule out the active galaxies and stars that dominate X-ray surveys [7]. The third criterion reflects the proximity of the sources (with maximum distances of  $\sim 1$  kpc) and the large space velocities of known neutron stars [2, 8]. The final criterion comes

from the Galactic nature of the sources, and is similar to the distribution of radio pulsars.

## The Legacy of *ROSAT*

While some had anticipated up to 5,000 objects discovered through soft X-ray surveys [4, 5], the *ROSAT* All-Sky Survey (RASS) discovered just over half a dozen<sup>1</sup> (as of 2007) nearby cooling neutron stars (see Tab. 1). These neutron stars are then all the more valuable because of their rarity.

The first such source to be discovered was RX J1856.5–3754 (hereafter RX J1856). It was originally identified serendipitously as a soft, bright X-ray source with no obvious optical counterpart [12]. Its location in front of the R CrA molecular cloud meant that it had to be nearby ( $\lesssim 200$  pc [13]) and hence small (not a white dwarf or anything larger)—otherwise the X-ray emission would have been absorbed<sup>2</sup>. Confirmation of its nature came with the discovery of a very faint ( $m_B \approx 25.8$  mag), blue optical counterpart [17].

Since then, six other similar sources have been identified with considerable effort [37, 42–46]. While a variety of names and acronyms exist for these objects, we call them simply “Isolated Neutron Stars” (INS). Identification of additional sources that may still be present [47] in the *ROSAT* Bright Sources Catalog (containing  $\approx 18000$  sources with  $> 0.05$  counts s $^{-1}$  with the

<sup>1</sup> The difference is largely from poor assumptions about the pulsar velocity distribution [6, 9] and the effects of magnetic fields [10, 11].

<sup>2</sup> As it turned out, this argument was false, as observations of more distant stars did not have high extinction [14]. Nonetheless, RX J1856 is quite close [15, 16].

**TABLE 1.** Observed Properties of the Seven Isolated Neutron Stars

RX J	Spin*			Spectrum <sup>†</sup>					Astrometry**		References
	P	$\dot{P}$	PF	$N_{H,20}$	$kT$	PN	$E_{abs}$	$m_B$	$\mu$	d	
	(s)	( $10^{-14}$ )	(%)	( $cm^{-2}$ )	(keV)	( $s^{-1}$ )	(keV)	(mag)	( $mas\ yr^{-1}$ )	(pc)	
1856.5–3754	7.06	...	1	0.8	62	8.3	...	25.2	333	160	14, 15, 18–20
0720.4–3125 <sup>‡</sup>	8.39	7	11	1.0	87	7.6	0.3	26.6	97	360	21–26
1605.3+3249	...	...	< 3	0.8	93	5.6	0.5(0.6,0.8)	27.2	155	390	27–31
1308.6+2127	10.31	11	18	1.8	102	2.5	0.2(0.4)	28.4 <sup>§</sup>	200 <sup>¶</sup>	...	32–36
2143.0+0654	9.44	...	4	3.6	102	2.0	0.7	> 26 <sup>  </sup>	...	430	37–39
0806.4–4123	11.37	...	6	1.1	92	1.8	0.3(0.6)	> 24	...	250	29, 40
0420.0–5022	3.45	...	17	2.1	45	0.2	0.3	26.6	...	345	29, 40

\* We give the spin-period, period derivative, and rms pulsed fraction.

<sup>†</sup> We give the hydrogen column density, blackbody temperature, *XMM-Newton* EPIC-pn count-rate, central energy of any absorption features in the X-ray spectrum, and *B*-band magnitude. We also give energies of any secondary lines, if known. Note that all spectral estimates are covariant, and that the details of the X-ray absorption depend on the specific model.

\*\* We give the proper motion and distance, using the parallax if known, else that inferred from Posselt et al. [41].

<sup>‡</sup> The spectral parameters are average quantities.

<sup>§</sup> Inferred from STIS 50CCD.

<sup>¶</sup> Based on Motch et al., these proceedings.

<sup>||</sup> Inferred from *V* and *r'* bands.

Position-Sensitive Proportional Counter, or PSPC; [48]) is extremely difficult given the poor positional accuracy of the PSPC. We will return to this later.

## OBSERVED PROPERTIES

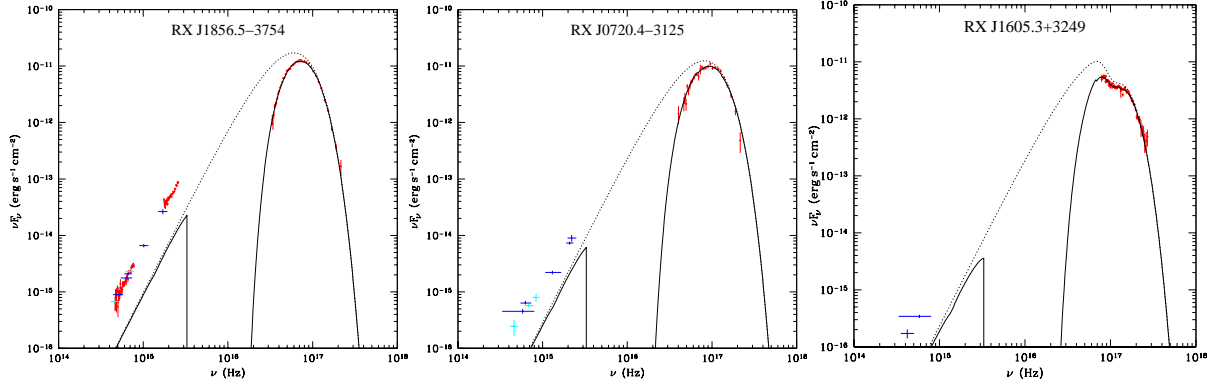
We summarize the properties of the 7 confirmed INS in Table 1: also see previous reviews such as Haberl [29], that give additional observational details. The basic properties largely bear out the expectations of Treves and Colpi [4] but with much smaller numbers: they are soft X-ray sources with faint optical counterparts and significant proper motions. However, there are too few of them to see a concentration in the Galactic plane, and they may actually reflect a more local population that was born in the Gould Belt [49].

The X-ray spectra of the INS are reasonably close to soft black bodies with  $kT$  in the range of 40 to 100 eV [18] attenuated by a small amount of interstellar absorption (Fig. 1). There is no sign of any non-thermal X-ray power-law such as those seen in the spectra of most radio pulsars. Most of the INS, however, have spectra that appear with significant absorption features at low energies (Fig. 1) [26, 28, 34, 38, 40]. Typically, the absorption is modeled as one or more broad absorption lines, although the line shapes are complex and phase-dependent, and as we obtain increasing amounts of data our initial fits are no longer sufficient. All but one of the INS have hints of absorption in their spectra, and several [29, 36] may even have absorption at multiple energies. Posselt et al. [41] used the measured column densities, along with a map of the local interstellar medium, to infer distances to

the INS. They found the objects were nearby ( $\lesssim 500$  pc, generally), although we note that it can be difficult to establish a reliable column density when the intrinsic form of the spectrum is not well known [e.g., 50].

All but one of the INS show gentle, largely sinusoidal X-ray pulsations, although some may be double-peaked [35]. The periods are all tightly clustered (compared to radio pulsars) between 3 and 11 s (Fig. 2), and the pulsed fractions vary from  $\sim 1\%$  to almost 20%. Through repeated X-ray observations we have been able to establish reliable, phase-connected timing solutions for two of the INS, RX J0720.4–3125 (hereafter RX J0720) and RX 1308.6+2127 (hereafter RX 1308), and we find spin-downs of  $\sim 10^{-13} s\ s^{-1}$ . With the period derivatives, we can calculate the usual pulsar quantities [51]: dipolar magnetic field  $B_{dip} = 2.4$  and  $3.4 \times 10^{13}$  G, characteristic age  $\tau = 1.9$  and 1.5 Myr, and spin-down energy loss rate  $\dot{E} = 4.7$  and  $4.0 \times 10^{30} erg\ s^{-1}$  for RX J0720 and RX 1308, respectively [23, 33].

In the optical and ultraviolet, deep searches have revealed confirmed counterparts to four of the INS [17, 27, 32, 52, 53], and a possible counterpart to a fifth [40]. In keeping with the identification of these objects as neutron stars, the optical counterparts are quite faint (far fainter than any possible companion might be), with X-ray to optical flux ratios of  $\sim 10^4$ . However, the optical fluxes generally lie a factor of  $\sim 10$  above the extrapolation of the X-ray spectrum (Fig. 1): the so called “optical excess.” In the best studied case, RX J1856, the optical/UV spectrum is consistent with the slope of a Rayleigh-Jeans tail:  $F_\nu \propto \nu^2$  [14]. In the other cases we do not have nearly as much data and the inferences are consequently less certain. For RX J0720, the opti-



**FIGURE 1.** Spectral energy distributions for RX J1856 (left), RX J0720 (center; with the X-ray spectrum from before the appearance of an absorption feature), and RX J1605 (right). For the first two, the X-ray points are from *Chandra*/LETG spectra [18, 21], and for RX J1605 the X-ray points are from *XMM-Newton*/RGS [28]. The optical data are from a combination of ground-based and space-based observations [14, 27]. The solid curves represent the best-fit black-body models to the X-ray data (with an absorption feature in the case of RX J1605); the dotted curves are the same model without interstellar extinction.

cal/UV spectrum is close to the slope of a Rayleigh-Jeans tail, but there are indications that it deviates [21, 22]. For RX J1605.3+3249 (hereafter RX J1605), the data are even sparser, but it might have even larger deviations from a Rayleigh-Jeans tail [30].

An elongated H $\alpha$  nebula surrounding RX J1856 was found by van Kerkwijk and Kulkarni [54]. The nature of this nebula is not entirely clear, but it is likely a bowshock formed by the interaction between the neutron star’s energetic wind and the interstellar medium through which it is traveling supersonically [e.g., 55]. In this model, we can infer  $\dot{E}$  for RX J1856 even though  $\dot{P}$  has not been measured, and find  $\dot{E} \gtrsim 1.2 \times 10^{33} d_{160}^3 \text{ erg s}^{-1}$  (where the distance is  $160 d_{160}$  pc). Motch et al. [30] discovered some evidence of H $\alpha$  emission from the position of RX J1605, but it has yet to be confirmed.

Proper motions have now been measured for four of the INS [15, 22, 24, 30, and Motch et al., these proceedings]. The implied transverse velocities are generally  $\sim 200 \text{ km s}^{-1}$ , consistent with the pulsar population. Tracing the proper motions back, one finds that these INS are consistent with being born in nearby OB associations  $\sim 1 \text{ Myr}$  ago [56]. We have also been able to measure parallaxes to two of the INS. The distances are largely consistent with those estimated by Posselt et al. [41].

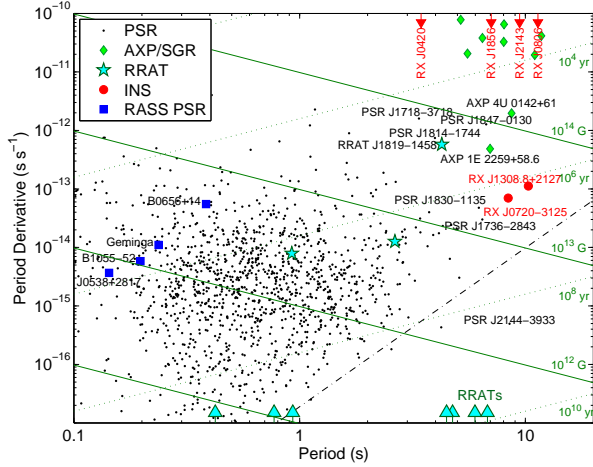
In the radio, there are no confirmed detections of any INS as a steady radio source or via pulsations [21, 27, 32, 57]. Motivated by the similar location in the  $P - \dot{P}$  diagram of the INS and the Rotating Radio Transients (RRATs; [58]), there have also been searches for sporadic radio bursts from the INS, and these too have been negative [see Burgay, Kondratiev in these proceedings]. Similarly, searches for counterparts in the near-infrared (where one might see emission from a faint companion or an accretion disk) have not been successful [59].

## INFERENCES & ENERGY SOURCES

From the general properties of the INS discussed above, it seems clear that the INS are reasonably young ( $\sim 1 \text{ Myr}$ ) isolated neutron stars. The X-ray emission that we see is plausibly thermal: the values of  $\dot{E}$  that we measure or infer are all quite low, compared to X-ray luminosities of  $\sim 3 \times 10^{32} d_{360}^2 \text{ erg s}^{-1}$  (for RX J0720 [21], where we normalize to a distance of  $360 d_{360}$  pc). In contrast to radio pulsars (and other rotation-powered objects such as Geminga), which have  $L_X \sim 10^{-3} \dot{E}$  [60, 61] and where rotational energy powers the majority of the X-ray emission (some may be thermal), RX J0720 has  $L_X/\dot{E} \sim 60$ . Therefore, for RX J0720 rotation *cannot* power the X-ray emission, and we must resort to other mechanisms. While the value of  $\dot{E}$  inferred for RX J1856 from the H $\alpha$  nebula is of a different order than those for RX J0720 and RX 1308, it is still much less than what would be necessary to contribute significantly to the X-ray emission. However, unlike for RX J0720 where the age inferred from timing is close to the kinematic age, using the inferred  $\dot{E}$  for RX J1856, its spin period, and kinematic age it is hard to form a consistent picture, something we are investigating.

The remaining energy sources that we must consider are accretion, magnetic fields, and thermal energy, all of which are seen in other types of neutron stars.

Models involving accretion from the ISM for the INS [e.g., 62] have essentially been ruled out as energetically important: the high velocities ( $\sim 200 \text{ km s}^{-1}$ ) inferred for RX J1856 and RX J0720 from their proper motions and parallaxes [15, 24] make Bondi-Hoyle accretion ( $\dot{M} \propto v^{-3}$ ) very improbable, especially with the ISM density for RX J1856 inferred from the H $\alpha$  nebula [54]. We can then examine accretion from a fossil



**FIGURE 2.** A portion of the  $P$ - $\dot{P}$  diagram, showing radio pulsars (points; [65]), magnetars (diamonds), and the newly-discovered rotating radio transients (RRATs [58]; stars and arrows at bottom); selected objects are labeled, and the pulsars with  $> 0.05 \text{ s}^{-1}$  in the RASS are shown as the squares. Also shown are the INS: RX J0720 and RX J1308 by filled circles, and the others by arrows at the top (since  $\dot{P}$  is unknown). The diagonal lines show loci of constant dipole magnetic field (solid) and spin-down age (dotted), while the dot-dashed line is an approximate “death-line” for pulsar activity. The similarity in spin properties between the INS and some of the RRATs was noted by McLaughlin et al. [58] and Popov et al. [66].

fall-back disk [63, 64]. Timing observations of RX J0720 limit the torques from a disk such that  $\lesssim 1\%$  of the observed X-ray luminosity can come from frictional heating, and having accretion penetrate the centrifugal barrier to land on the surface would require an unreasonably large accretion rate of  $\dot{M} \sim 2 \times 10^{17} \text{ g s}^{-1}$  [also see 59].

Excluding accretion as an energy source, we are left with residual thermal energy and magnetic fields. All neutron stars should have thermal energy powering emission at some level, but only those with magnetic fields high enough to decay ( $\gtrsim 10^{14} \text{ G}$ , generally) will have significant magnetic luminosity [67].

Heyl and Kulkarni [67] proposed a model where RX J0720 was heated by magnetic field decay. This would help explain the similarity between the spin-period of RX J0720 and those of magnetars [68], and it would also explain why objects like RX J0720 could be overrepresented in a local sample. However, timing observations of RX J0720 suggest that the magnetic field was not ever strong enough to decay significantly [69, 70].

We are then left with cooling. The X-ray emission from the INS is consistent (given the many uncertainties) with that expected for standard cooling [e.g., 71], and spectral modeling finds no detectable evidence for non-thermal emission. This is largely consistent with the

observed  $\dot{E}$  and X-ray luminosity, as discussed above. Indeed, for most young neutron stars the X-ray emission that we see is some combination of cooling and rotation [e.g., 72], with the relative fractions varying depending on source age,  $\dot{E}$ , and distance (for the more distant sources, interstellar absorption tends to remove traces of soft thermal emission first). Zane et al. [69] and Kaplan et al. [70] suggested that RX J0720 (and the rest of the INS) were in fact rotation-powered pulsars either without radio emission or where the radio beam does not cross our line of sight (consistent with the very narrow beams found for long-period pulsars [73–75]), but where we do not actually see any of the non-thermal emission. This is consistent with the interpretation of the  $H\alpha$  nebula around RX J1856 as a bow-shock, which requires an energetic particle wind to come from the neutron star (presumably as a result of spin-down). The small deviations of RX J0720 from a Rayleigh-Jeans spectrum in the optical may be a hint of a non-thermal power-law peaking out, or they may just reflect our lack of understanding of the intrinsic spectrum. The spin characteristics of the INS are unusual compared to the bulk of the pulsar population but are not entirely unheard of — we will return to how the INS relate to the pulsar population later.

## THE UTILITY OF THE INS

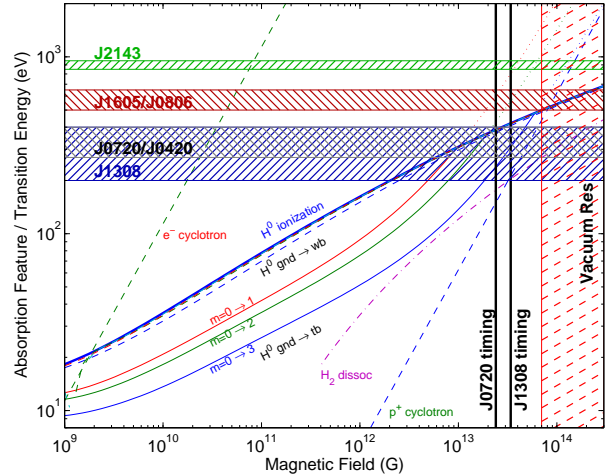
Accepting that the INS are nearby, cooling neutron stars with moderate ( $\sim 10^{13} \text{ G}$ ) magnetic fields and cold ( $kT \lesssim 100 \text{ eV}$ ) surfaces, the sources take on importance beyond their contribution to the local neutron star population. We can use the INS as “physics laboratories,” probing regimes of physics not accessible experimentally (or sometimes even theoretically [76]). There are three areas where we can hope to derive meaningful physical constraints from or explore novel regimes with the INS: (1) neutron star radius measurements; (2) neutron star cooling; and (3) strong magnetic fields. While measurements of other neutron stars can be used to address these issues, often providing complementary constraints [many explored in these proceedings], the INS are particularly well-suited. This is because they are nearby, young, and have no detectable non-thermal emission. Therefore they are bright, can still constrain cooling models, and have emission that is less susceptible to arbitrary decomposition than many rotation-powered pulsars.

The first two physical constraints come about because of our relative ignorance about the details of the equation of state (EoS) of matter at super-nuclear densities and for neutron-rich systems, such as those one finds in the interiors of neutron stars. We do not know some of the basic properties of such matter such as the constituent particles, and options ranging from basic super-nuclear matter to pion or kaon condensates to color-superconducting quark

matter are all possible. With each of those possibilities comes a range of predictions for the overall mass and radius of the neutron star, but one finds that the radius is largely independent of the mass (at least for masses near the canonical value of  $1.4 M_{\odot}$ ), so that a radius measurement has the hope of constraining the physical models of the neutron star interior [76, 77]. At the same time, the detailed predictions for the interior lead to different microphysical processes that affect the overall cooling of the neutron star, so knowledge of how neutron stars cool can also be used to constrain the interior [71, 78].

To constrain the radii or cooling properties of the INS, there are a number of observational quantities that we need to understand. For cooling, the goal is to place the INS on a plot of luminosity versus age<sup>3</sup>. The ages can be estimated through two methods: either tracing the neutron stars back to likely birth locations, or through standard pulsar spin-down assumptions. While we would expect both of those methods to have uncertainties, the first is less likely to be systematically wrong. Indeed, the spin-down ages for RX J0720 and RX 1308 are 1–2 Myr, compared to kinematic ages of  $< 0.7$  Myr measured for those and two other sources. This could be a coincidence, but it does mean that we should be cautious in using the spin-down ages (also see, e.g., [80]). The luminosity needs both a distance (measured through astrometry or estimated from absorption column densities) and an accurate flux measurement. However, as discussed in Page et al. [79], the influence of the neutron star’s envelope on the emergent spectrum and the cooling behavior is such that we also need to understand the elemental abundances, surface temperature distribution, and magnetic field distribution over the surface (also see [78, 81, Yakovlev, these proceedings]). This last item has been the most difficult, and we will return to it below. Radius measurements need essentially the same data, although we do not need an age. But accurate distances and flux measurements are just as important, and again our ignorance of the surface composition etc. limit any possible conclusions [82, 83].

Investigating magnetic fields is a more tractable problem. Instead of the Quantum Chromodynamics (QCD) in the neutron star interior, where the current theory leaves many areas unknown [84], the magnetic fields manifest Quantum Electrodynamics (QED) which is difficult but solvable in this regime. Here it is not so much that we use the neutron stars to constrain physics as we have two-way feedback between the theory and the observations. The physical phase of the surface material can be strongly affected by the magnetic field [85], and the mag-



**FIGURE 3.** Energy versus magnetic field for electron and proton cyclotron, ground state to tightly bound (tb) or weakly bound (wb) states in neutral hydrogen, hydrogen ionization, and molecular  $H_2$  dissociation [87–89]. For fields above  $\sim 10^{14}$  G (hatched region to the right), features may partly be washed out due to the effects of vacuum resonance mode conversion [90]. The hatched bands show the absorption feature energies (corrected for gravitational redshift) for the INS (Table 1). We argue [20] that the features in most sources are due to neutral hydrogen (at least in part), the only exception being RX J2143, which has the highest energy, and for which proton cyclotron absorption appears more likely. Qualitatively, the field strengths determined by timing for RX J0720 and RX J1308, indicated by the vertical lines, are consistent with our identifications.

netic field also affects the radiation propagating through it. The vacuum is polarized, and density gradients can lead to transitions between the polarization states that have significant effects on the total spectrum [86]. Again, these are areas where the fundamentals are known, but there are no terrestrial tests to the theory in these regimes and hence observations of neutron stars form the best application of these effects.

## OPEN QUESTIONS

### Understanding the Atmospheres

Initial attempts to model the X-ray spectra of the INS focused on blackbodies [56, 91], as they gave adequate fits and were simple. Including the optical/UV data it was clear that a single blackbody would not fit the data. Instead, two blackbodies were used, where a hot, small surface fit the X-ray data and a cooler, large surface fit the optical/UV [21, 92]. However, detailed applications of these models did not work, especially when one considered the phase-dependent spectral evolution [35, 93], and

<sup>3</sup> We could also do temperature versus age, although there are substantial difficulties in converting reliably between effective temperature and observed temperature [79].

such models are not physical.

Instead we must consider more realistic models, taking into account our latest knowledge of the X-ray spectra plus any additional constraints such as dipole magnetic fields from X-ray timing. In interpreting the spectra, a major uncertainty is the composition. For a single source, this may be difficult to determine uniquely, but one can hope to make progress by treating the INS as an ensemble: ideally, it should be possible to understand the features (or lack thereof) in all INS with a single composition, appealing only to differences in temperature and magnetic field strength (constrained by observations where possible), which might lead to different ionization states being dominant, and possibly the formation of molecules or even a condensate [87, 94].

There are a range of possibilities to explain the overall spectra and the X-ray absorption features of the INS. For the absorption, the simplest models are either proton cyclotron resonances or bound states of hydrogen, although other species are of course possible (though possibly more difficult to explain, as gaseous atmospheres composed of heavier elements appear to be excluded by the lack of large numbers of features, and any hydrogen should float to the surface).

We [20] have attempted to determine which species and magnetic field is dominant for each of the INS, based on the energies, strengths, and widths of the absorption features (Fig. 3). We can find a moderately self-consistent picture, with both proton cyclotron and hydrogen contributing. This picture agrees reasonably well with the magnetic fields inferred from X-ray timing although it was conceived independently. However, it is incomplete in at least two aspects. First, the evidence for multiple absorption lines [29, 36] does not fit into the scenario easily. Second, the evolution in the spectrum of RX J0720 is also not understood. See van Kerkwijk and Kaplan [20] for more discussion of both of these aspects, as well as more general issues.

In order to fit both the X-ray and optical data simultaneously, Motch et al. [22] and Turolla et al. [95] considered models that have condensed, blackbody-like surfaces, where Motch et al. [22] also includes a thin layer of hydrogen that is optically thin at X-ray energies but not at optical. Getting a condensed surface is possible for this range of magnetic field and temperature [85, 96], although it depends on the composition and the magnetic field distribution. Including the thin layer of hydrogen and varying the magnetic field allow for tuning of the optical excess to match observations. Indeed, Ho et al. [83] have updated this model to include partially-ionized hydrogen and found a reasonable fit to the phase-averaged spectrum of RX J1856 as well as the amplitude and shape of its pulsations [97], making this a promising avenue of investigation. However, we must still consider a number of issues addressing the physical reality of these models:

How did such a thin layer form? Is it stable? Will it persist? Why are the layers of roughly the same thicknesses for different sources?

## Evolution of RX J0720

While the initial observations of RX J0720 showed a smooth, blackbody-like X-ray spectrum [21, 91], later observations showed evidence for a phase-dependent absorption feature [26]. This discrepancy was first ascribed to increased sensitivity and better calibration of later observations, but de Vries et al. [98] realized that RX J0720 was actually evolving over the course of months. The spectrum was changing, with the blackbody getting harder at the same time as low-energy absorption appeared, such that the flux was relatively constant. Simultaneously, the pulse profile evolved to increase the pulsed fraction [99]. The change happened over the course of several years, but the majority of the variation occurred over the time span of a few months, from May to October of 2003.

These observations were very puzzling, as RX J0720 was not expected to vary on such time scales. Two sets of models were considered to explain the data [98]: either the intrinsic spectrum of RX J0720 changed, or the angle at which we view the object change. They conclude that the second model is more likely, as no obvious physical motivation could be found for the first. Instead, free precession [100] could be operating. Haberl et al. [101] find further support for this model by fitting additional data and observing that the spectral changes seem to be reversing themselves after several years; they suggest a timescale of  $\sim 7$  yr for the precession, although note that this was with only  $\sim 5$  yr of spectral data, so the timescale was not well constrained. If true, this would have important implications for our study of the superfluid states in the object's interior [100].

However, other models are still possible. We have investigated the spectral data and the timing data together [25], and find evidence that the changes in the spectrum appear more impulsive than periodic and were accompanied by a simultaneous jump in the spin frequency, with a fractional increase of  $5 \times 10^{-8}$ . Instead of precession, we interpret this as evidence for an sudden change on the neutron star surface accompanied by a simultaneous torque, followed by a slow relaxation back to the original spectrum. We have considered a number of mechanisms, from typical pulsar “glitches” that would release energy in the neutron star interior, to reconfiguration of the magnetic field leading to changes in both the spin-down and in the temperature/emergent spectrum of the surface, to accretion of small amounts of material onto the neutron star surface that would both torque the star and change



the composition. No mechanism is fully satisfactory, but we are attempting to include constraints from modeling the phase-dependence of the spectrum to try to understand the situation better [Mori et al., in prep]. We are also looking for similar behavior in other sources, but so far they seem stable [Airhart et al., these proceedings].

## Relation to the Pulsar Population

If we consider that the INS are moderately young neutron stars with  $\sim 10^{13}$  G magnetic fields, we must ask what separates them from the bulk of the rotation-powered pulsar population and what their relation to that population is. To gain insight, we can compare with two groups of objects. First, the other pulsars found with comparable count rates ( $> 0.05 \text{ s}^{-1}$ ) in the RASS, and second, the known pulsars with  $B \gtrsim 10^{13}$  G.

As highlighted by its use is discovering the INS, the RASS is an efficient and relatively unbiased way to find young neutron stars. All neutron stars should shine in soft X-rays, either via cooling radiation or non-thermal processes. Taking only the thermal emission, which should persist as a baseline, the effects of beaming are quite minor (compared to radio pulsar searches). Aside from the 7 INS, there are 8 other Galactic pulsars with comparable count-rates [based on 60, 61, 102]. These include many of the best-known pulsars: the Crab pulsar, the Vela pulsar, PSR B0656+14, Geminga, and PSRs 1055–52, J0437–4715, B1951+32, and J0538+2817 (in order of decreasing count-rate; see squares in Fig. 2). Of these, the Crab is much younger and more energetic than the others but is significantly more distant, and PSR J0437–4715 is an old recycled pulsar. The remaining objects are moderately young and nearby, much like the INS. However, the INS all have periods  $> 3$  s (known for 6 of 7), while the other pulsars all have periods  $< 0.4$  s. Not only that, but the other pulsars all have detectable non-thermal X-ray emission. In fact, if we look at the characteristics that define the INS — young, nearby, X-ray bright, long periods — we cannot find any other pulsars in the ATNF catalog [65] that match them. The INS are obviously then a significant subpopulation of objects, representing as many as half of the observed neutron stars within  $\sim 500$  pc. The number of detected INS compared to the number of young pulsars in the same volume implies a very large total number of similar sources in the Galaxy. There have been a number of population estimates [e.g., 49, 66] that try (with moderate success) to explore this quantitatively, but they are limited by the small number of sources. However, we must still explain why there are so many INS with similar periods (and presumably ages and magnetic fields) in such a small volume. The idea of Heyl and Kulkarni [67],

that magnetic-field decay could lead to a preponderance of nearby old magnetars, is certainly worth examining. While as discussed above the INS do not seem to have been true magnetars in the past, these conclusions used simple models for field decay (something still not understood in detail), and they assumed that the internal field was comparable to the dipolar component. If there are significant toroidal components to the field, these may be strong enough to decay but would not affect spin-down. Therefore, the INS could have some contribution to their X-ray luminosity from magnetic field decay, or magnetic fields could alter standard cooling behavior if they are strong enough to influence the heat conduction through to the surface [81].

If we look further afield for objects that more closely resemble the INS, we find the so-called high- $B$  radio pulsars (HBPSRs). These sources are largely emerging in the last seven years and their population is probably not complete, but we see examples with dipolar fields of several  $\times 10^{13}$  G, almost up to  $10^{14}$  G [103–105]. Some of the magnetic fields are actually higher than those of the INS, but the distribution of sources with respect to  $B_{\text{dip}}$  (Fig. 2) seems mostly continuous leading up to and past RX J0720 and RX 1308. The HBPSRs are younger than the INS, but tend to be much more distant and have higher values of  $\dot{E}$ /X-ray luminosity (when detected). This last fact could possibly be explained just through the usual models for pulsar evolution: assuming a constant magnetic field, then  $\dot{E}$  evolves as  $B_{\text{dip}}^{-2} t^{-2}$ , so the difference of a factor of roughly  $10^2$  in age would correspond to  $10^4$  in  $\dot{E}$ . This would then give values consistent with those for the INS. At the same time, as  $\dot{E}$  dropped the dominant source of X-ray emission became the residual thermal emission that we see from the INS instead of the power-law emission that we see from the HBPSRs (and from other active pulsars).

The INS may then represent a population of evolved HBPSRs [69, 70]. Previous analyses of pulsar populations have usually not required pulsars beyond magnetic fields of  $10^{13}$  G or so [e.g., 106–108], but it now seems apparent that the true distribution extends further in significant numbers (a conclusion also becoming apparent just from recent pulsar surveys; [1, 2]).

As discussed above, there are no detections of radio emission (pulsed or continuous) for the INS. The flux limits are reasonably low, and coupled with the small distances to the INS the luminosity limits are orders of magnitude below the luminosities of the faintest known radio pulsars (such as PSR J0205+6449 in 3C 58; [109]). The non-detection of radio emission from the INS could be explained by the very narrow radio beams found for long-period pulsars/HBPSRs ( $\lesssim 1\%$  [73, 105]); this has led to large uncertainties in the predicted number of long-period sources [e.g., 108]. At the same time, the

rapid evolution of the HBPSRs across the  $P - \dot{P}$  plane may drive them across the “death line” and terminate radio activity quickly, so that the objects we see may no longer be radio sources at all. We also look to the sporadically emitting RRATs, some of which seem to have similar spin characteristics to the INS and which may be a related population [66].

## DISCOVERING NEW SOURCES

With such a limited sample, the INS are invaluable for individual investigations but have only limited use as a population. In addition, each object has its own peculiarities and pathologies, which make comparison with the rest of the sample difficult. For instance, of the two brightest objects, RX J1856 lacks an X-ray absorption feature but has an H $\alpha$  nebula, while RX J0720 varies.

To help remedy this situation, for several years intensive efforts have been underway to identify new isolated neutron stars [47, 110, Pires et al. in these proceedings]. This is a difficult and time-consuming task, given the need to cross-identify X-ray sources (which often have poorly known positions) with optical catalogs, rejecting those sources that have plausible counterparts [e.g., 111].

Currently, the majority of these efforts have yet to produce significant results, but the first few good candidates are emerging. Using the *SWIFT* satellite, Fox [112] is improving the positions of *ROSAT* sources, which facilitates the search. Based on this, Rutledge et al. [113] have identified a source which appears to be a neutron star, although not necessarily of the same type (young, thermally emitting) as the INS. Pires et al. [these proceedings] may have identified another from *XMM-Newton* data, although given how faint and absorbed that object is likely to be, confirming it as a neutron star with deep optical observations will be very difficult, and X-ray data will only yield limited information. Even so, as more of these objects come to light they can help us construct more reliable population estimates for the INS and establish their relation to the greater neutron star population.

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